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M.S. Gussenhoven, D.A. Hardy, F.J. Rich, E.G. Mullen, R.H. Redus

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Evidence that Polar Cap Arcs Occur on Open Field Lines

M. S. GUSSENHOVEN, D. A. HARDY, F. J. RICH, E. G. MULLEN, and R. H. REDUS

United States Air Force Geophysics Laboratory, Hanscom Air Force Base, Massachusetts, U.S.A.

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The characteristics of polar cap arc occurrence are reviewed to show that the assumption of a closed magnetospheric magnetic field topology at very high latitudes when the IMF B_z is strongly northward is difficult to reconcile with a wide variety of observational and theoretical considerations. In particular, we consider the implications of observations of particle entry for high and low energy electrons, magnetic flux conservation between the near and far tail, the time sequencing in polar cap arcs events, and the hemispherical differences in polar cap arc observations. These points can be explained either by excluding the need for a major topological magnetic field change from explanations of polar cap arc dynamics, or by assuming a long-tailed magnetosphere for all IMF orientations in which magnetic field lines eventually merge with solar wind field lines in either a smooth or a patchy fashion.

1. Introduction

In recent years a variety of statistical and case studies have been reported that describe magnetospheric processes occurring when the interplanetary magnetic field (IMF) has a large, northward component and auroral arcs are observed in the central polar caps. For many of these studies researchers have assumed, or used their results to conclude, that the magnetospheric magnetic field topology is closed over all, or a large portion of the polar caps for these conditions. Indeed, one may say that this is the prevailing view in the field today. Notable exceptions are provided by CHIU (1989) and GUSSENHOVEN and MULLEN (1989).

The principal reasons for the popularity of the closed magnetosphere view are two: a) Having closed polar cap field lines for IMF northward and open polar cap field lines for IMF southward offers the possibility of a distinction in the magnetospheric dynamics of the two states, and a distinction is certainly observed. For IMF southward, auroral activity is confined to the oval and the polar cap is "empty". For IMF northward, auroral oval activity is greatly reduced, and auroral arcs appear across the polar caps. b) A closed magnetic field topology apparently explains why electrons with keV energies are found for long periods of time (hours) in the central polar caps. These electrons accompany and create visible polar cap arcs. Electrons trapped on closed field lines are subject to greater heating during their many bounce periods compared to electrons on open field lines which have less than a 1/4 bounce period. The reasoning here is much the same as that which describes discrete oval arcs as occurring on closed field lines.

We believe that the assumption of a closed (or nearly closed) magnetosphere for northward IMF has been too readily accepted and that other empirical findings are more consistent with an open field line topology. By open field line topology we mean one in which magnetic field lines over a substantial portion of the polar cap extend downtail to large distances (>500 R_E) where they merge or intermingle with interplanetary field lines. The object of this paper is not so much to make the case that the magnetosphere remains open for all IMF conditions, as to point out that by closing distant field lines one, at best, makes no progress in understanding polar cap arc dynamics, and at worst, creates a variety of inconsistencies. We review several recent polar cap arc studies to this end. We suggest that more headway is gained by leaving the magnetic field topology more or less constant and examining magnetosheath ion entry and convection in the tail lobes under IMF northward conditions while requiring electrons to maintain conditions of quasi-charge-neutrality.

2. High- and Low-Energy Electron Boundaries in the Polar Caps

Two electron populations are commonly used to demarcate the high latitude region of open field lines: relativistic solar electrons and polar rain. Historically, the relativistic electron population that accompanies solar proton events was first used to this end. Within the magnetosphere the low altitude profile of these electrons is often extremely flat across both polar caps and the intensity level responds promptly to changes in the intensity of interplanetary electrons. An example of solar electron precipitation in the southern polar cap is given in the top panel of Fig. 1, where the intensity of >1 MeV electrons is plotted for a high latitude pass of the DMSP/F7 satellite (at 840 km) during the period of the great storm in February, 1986. This figure is taken from a polar cap arc case study by GUSSENHOVEN and MULLEN (1989). The region in which the relativistic electrons are found in Fig. 1 is in good general agreement with the open field line region determined by other magnetospheric particle populations, e.g., the region above the polar cusp on the dayside and above the central plasma sheet on the nightside. These features, combined with the observation that when the solar flare electrons have anisotropic pitch angle distributions the intensity levels in the polar caps of the two hemispheres differ, led researchers in the late 1960's and early 1970's to conclude that there is a high latitude region of open field lines that is directly accessed by high energy interplanetary electrons. Several researchers in this period also pointed out the insensitivity of the size of the open field line region, so defined, to changes in the direction of the IMF. See reviews by VAMPOLA (1974) and MORFILL and SCHOLER (1973) and references therein.

Solar proton events are rare and researchers have looked for a more constant external electron source to provide a measure of the open field line region on a regular basis. Polar rain (WINNINGHAM and HEIKKILA, 1974; see also the review by GUSSENHOVEN, 1989 and references therein), the weak, slowly varying, low energy electron population found throughout the polar cap for IMF B_z south conditions and exhibiting a hemispheric difference in intensity as a function of IMF B_y, has come to be used for this purpose. The assumptions here are that the polar rain source is the solar wind halo or strahl component (kT~80 eV) and that it directly enters the magnetosphere only along open field lines (FAIRFIELD and SCUDDER, 1985; BAKER et al., 1986). The polar rain fluxes are significantly less than oval fluxes because after one reflection at the mirror point the electrons escape again to the interplanetary plasma. Under these assumptions, the open-closed field line boundary is the equatorward boundary of polar rain. It follows from this reasoning that all auroral arcs, whether along the oval or in the polar caps, and all boundary layer populations, are on closed field lines. We take here the less restrictive

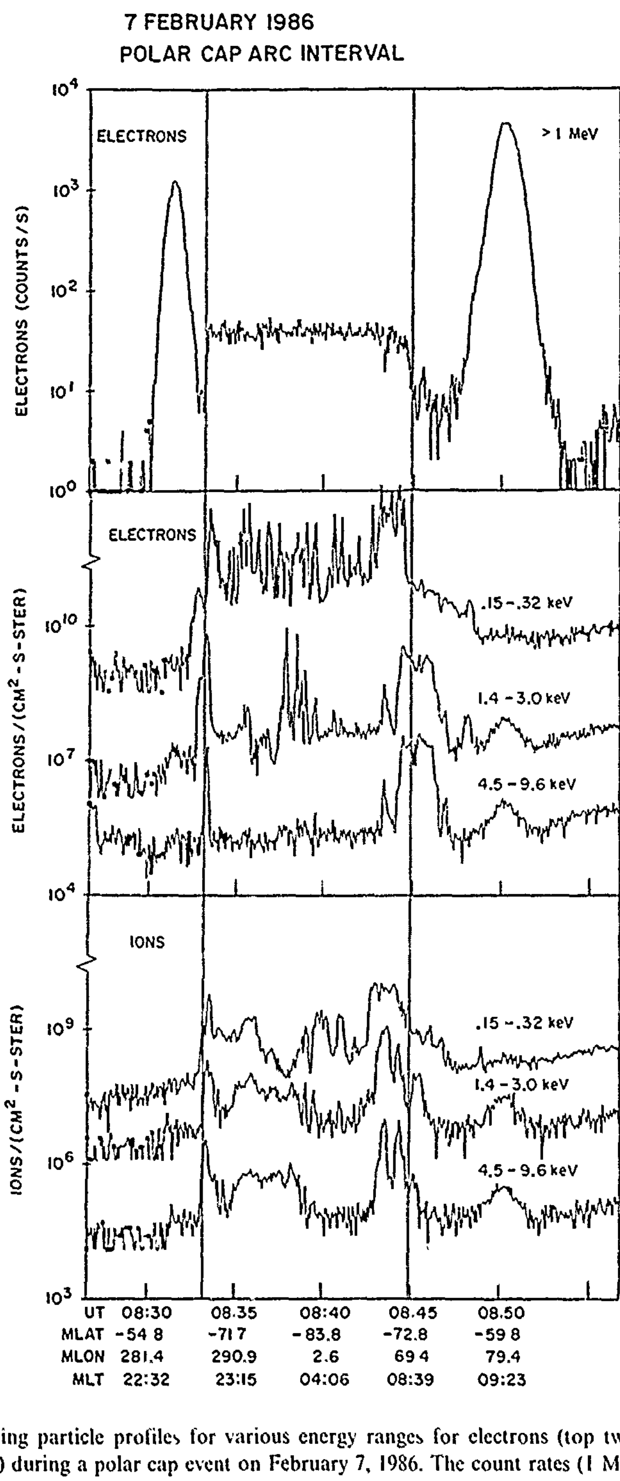

Fig. 1. Precipitating particle profiles for various energy ranges for electrons (top two panels) and ions (bottom panel) during a polar cap event on February 7, 1986. The count rates (1 MeV electrons) or the number flux are plotted against universal time, corrected geomagnetic latitude and longitude projected along field lines to 100 km, and magnetic local time.

view that, although polar rain is on open or greatly extended field lines, it does not necessarily provide the boundary of open field lines.

The polar cap arc event studied by GUSSENHOVEN and MULLEN (1989) and shown in Fig. 1 was unusual because it occurred during a solar proton event. In every other way it exhibited characteristics typical of polar cap arc events previously reported. However, the coincidence of the polar cap arc and solar proton event allowed Gussenhoven and Mullen to compare the relativistic electron and polar rain methods of determining the open field line region for strong B_z north conditions. In the middle panel of Fig. 1 precipitating electron flux profiles taken over various energy ranges are shown. Polar rain best shows itself as a smooth profile in the lowest energy range shown (.15–.32 keV). Although the DMSP satellite pass shown in Fig. 1 passed within 6° MLAT of the magnetic pole, there is no significantly long time interval (say, 1 min) in which polar rain can be identified. The absence of polar rain up to very high latitudes during polar cap arc events has been noted before (HARDY et al., 1982; FRANK et al., 1986). For the time period of Fig. 1, corresponding white light DMSP images show multiple arcs in the central polar cap. The location of the arcs correspond to the sharp, narrow spikes in the 1.4–3.0 keV electrons. Thus, for polar cap arc events the region of polar rain precipitation is small or non-existent. If this region is associated with the open field line region, or conversely, if polar cap arcs occur on closed field lines, one must conclude that the magnetosphere, during times of polar cap arc occurrence, is almost entirely closed.

The case study of Gussenhoven and Mullen clearly shows that the assumption that polar cap arcs occur on closed field lines is inconsistent with the assumption that relativistic electrons gain access to the magnetosphere on open field lines. In Fig. 1 the relativistic electron precipitation is uniform over a polar cap of radius greater than 20° MLAT, while the radius of polar rain is at most 6° (the highest latitude of the satellite). This lack of agreement may be attributed to transport processes involving one or the other population. Recent ISEE 3 measurements in the tail lobes by ZWICKL et al. (1984) show an increasing density in the low energy (<1 keV) electron population with increasing distance downtail. Furthermore, comparison of the flux of low energy electron population at 200 R_E to the polar rain flux at low altitudes shows significant differences, the former being substantially more dense than the latter (BAKER et al., 1987). GUSSENHOVEN (1989) has suggested that these measurements are consistent with a field-aligned potential drop taking place over the entire tail length, greatly complicating tail lobe dynamics. Hydromagnetic processes can move low energy electrons many earth radii across magnetic field lines in a distance, along field lines, of several hundreds of earth radii. On the other hand, it has proven to be an insurmountable task to do the same for low density relativistic electrons when confined to lengths on the order of the Earth's magnetotail (MORFILL and SCHOLER, 1973). Non-adiabatic motion in a region of low field magnitude, such as a neutral point, can produce some distortion from field-alignment, but not big enough or with sufficient regularity to explain the relativistic electron profiles.

In their study Gussenhoven and Mullen point out that during and following the polar cap arc event on February 7, 1989, the electron transition boundary is in far better agreement with the relativistic electron boundary than the polar rain boundary. In low altitude precipitating electron profiles, proceeding from low to high latitudes, the transition boundary occurs at the point that magnetosheath-like electrons (~100 eV) jump in intensity by an order of magnitude or more, while higher energy electrons remain at the same level or decrease. On the nightside the transition boundary marks the boundary between the central plasma sheet and the boundary plasma sheet, on the dayside it marks the equatorward boundary of the cleft population. On the dawn and dusk flanks the transition boundary is the boundary between the boundary plasma (low latitude boundary layer) and the central plasma sheet. In other words, the transition boundary marks the onset of boundary plasma around the oval, even though at different local times entry mechanisms of the boundary plasma differ. For the pass shown in Fig. 1, the electron transition boundaries are nearly identical to the relativistic electron boundaries (vertical lines). Both the transition and the relativistic electron boundaries move poleward when the IMF turns from southward to northward, but, by no means, to the extent of the polar rain boundary. In Fig. 1, for example, when B_z was northward, the transition boundary on the dawnside is at ~73° MLAT, while the polar rain boundary is greater than 84° MLAT, if it exists at all. LASSEN and DANIELSEN (1989) have also shown, in a statistical study, the more conservative motion of the transition boundary for quiet times when compared to the poleward boundary formed by discrete arcs.

3. Magnetic Flux Considerations

There are other measurements that show the electron transition boundary to be a better indicator of the closed-open magnetic field line transition than the polar rain equatorward boundary. HOLZER *et al.* (1986) quantified a two-step merging and reconnection process during substorms in terms of the open field line flux in the tail lobes. They assumed that during the growth phase, only dayside merging takes place. This adds flux to the tail lobes, and, therefore, increases the size of the polar cap. During the expansion phase, dayside merging continues as long as the IMF has a southward component. In addition, reconnection begins in the nightside plasma sheet which reduces the flux in the tail lobes. Thus, during the expansion phase the flux in the tail lobes is determined by the two competing processes. For our purpose here we are only interested in their calculations during the growth phases of two substorms chosen for CDAW 6 analysis.

HOLZER *et al.* (1986) calculated the amount of flux added to the tail lobes during the merging process in two ways. They first determined the flux added in terms of a merging rate, the magnitudes of the southward component of the IMF and the solar wind speed, and the width of the magnetosphere. Second, they determined the change in flux passing through the open field line region of the polar caps at low altitudes. The second method requires a time history of the low altitude open-closed field line boundary. They used the electron transition boundary, as defined above, for this boundary. The agreement between the two methods was found to be excellent when an independently determined merging rate was used. (The authors actually used the data from the growth phase of the substorm to calculate the merging rate, but then found it to be nearly identical to that determined previously in a completely independent manner using magnetopause displacement as a measure of flux added.) They also found that the same merging rate was applicable to the growth phase of each substorm.

Holzer *et al.* addressed the problem of using the polar rain boundary, as opposed to the electron transition boundary, in determining the open field line region. They found that the baseline flux level (pre-substorm) was six times lower using the polar rain boundaries than using the transition boundary. Thus by using the polar rain boundaries, the flux change during the substorm expansion phase would either be far greater than that estimated from dayside merging, or the merging rate would have to be reduced to a much smaller value than that found by independent determination.

To further convince themselves that the transition boundary gave a better measure of the open field line region Holzer *et al.* compared the open field line flux in the polar caps, calculated using the transition boundary, to the flux in the tail lobes, calculated from magnetic field measurements on the ISEE 1 satellite in conjunction with a tail flaring model using solar wind data. They looked at 23 cases characterized by magnetic quiet conditions. During quiet periods the discrepancy between the electron transition and polar rain boundaries is generally quite large. With the transition boundary they found agreement in the two flux calculations to within 15%. We note that for the cases of low geomagnetic activity they studied, the open field line flux, using the transition boundary, was in the range of $4\text{–}7 \cdot 10^8$ Wb. The polar rain boundary gave a pre-substorm open field line flux of $1 \cdot 10^8$ Wb.

More recently FAIRFIELD (1988) used the arguments of MENG (1981) and FRANK *et al.* (1986) that the open field line region in the low altitude polar caps is greatly reduced for quiet and/or B_z northward conditions to estimate, by conserving magnetic flux at high and low altitudes, the size of the tail lobe at 200 R_E. He used a contracted polar cap radius of 7.5° for such times, giving a tail lobe flux of $1.2 \cdot 10^8$ Wb. (Note that even this small cap is conservative compared to those cases wher no polar rain interval occurs, such as shown in Fig. 1, and is similar to the pre-substorm flux calculations of HOLZER *et al.* (1986) using polar rain boundaries.) At 200 R_E, for a tale lobe field strength of 7 nT and allowing for a region of closed field lines in the plasma sheet, he predicts a tail radius of less than 18 R_E in disagreement with actual deep tail measurements of the radius.

A study of magnetopause normals using ISEE 3 data during a prolonged period (1/2 day) of strong IMF B_y was made by SIBECK *et al.* (1985) to demonstrate that the distant magnetotail can be greatly flattened and twisted. Although this study is quite frequently cited (e.g., FAIRFIELD, 1988) little reference has been made of the fact that during a substantial portion of this period the IMF had an extremely large positive B_z value, as well. The period in which ISEE 3 magnetic field data were used to determine magnetopause normals was the first half of January 15, 1983. Hourly averaged values of the IMF B_z component, in solar magnetospheric coordinates, were positive from 00:00 UT to 01:00 UT and from 08:00 UT to 12:00 UT. The average value was negative from 01:00 to 02:00 UT. IMF data were not available for the remainder of the time interval (03:00–08:00 UT).

Quite independently of the SIBECK *et al.* (1985) study, GUSSENHOVEN *et al.* (1985) and REDUS *et al.* (1986) studied the polar cap arc event that occurred at the end of this same period. Figures 2(a) and 2(b) show a series of DMSP white light images taken over the northern polar region on January 15, 1983, during and following the Sibeck *et al.* modelling period. In these images midnight is near the top of the image, dusk to the lower right corner. For each image the time interval of the image is given in both UT hours and UT seconds (the images are separated by 100 min), as well as the closest approach to the magnetic pole along the sub-satellite track (a line across the center of the image from left to right) in corrected geomagnetic latitude. There is considerable variation in the auroral activity throughout the period. The day begins with moderate substorm activity shown in the first two images. In the third image (~04:00 UT) weak arcs extend to very high latitude and the diffuse aurora is weak and thick. In the next four images (05:00 UT to

10:00 UT) a series of moderately intense substorms occurs. The seventh image (at 10:00 UT) shows arcs extending into the polar cap from the dusk oval. The eighth and ninth images (12:00 UT to 14:00 UT) show an extraordinarily intense band of arcs across the central polar cap. The energetic electron energy flux in these polar cap arcs exceeded 10 ergs/cm^2 s at times, making it one of the most intense polar cap arc events seen in DMSP data.

One of the interesting aspects of the Sibeck *et al.* study is that in their modelling of the tail shape and size during this period, no comment is made to suggest high variability in the tail dimensions or magnetic flux. One would expect that if significant closing of field lines had taken place either early or late in their modelling period, when polar cap arcs were occurring, that the tail lobe size would have shrunk sufficiently for prolonged periods to require comment (e.g., to Fairfield's predicted 18 R_E).

If we use the modelled tail lobe size of Sibeck *et al.* for 09:00 UT-10:00 UT on January 15, 1983, and convert their elliptical shape into an equivalent circular area, the radius of the circle is 24 R_E. This is closer to the average tail size quoted by Fairfield (25–30 R_E) and modelled in a later paper by SIBECK *et al.* (1986) (equivalent circular radius for their average ellipse is 26.4 R_E) than the 18 R_E size estimated for quiet times. And, if we use the modelled tail lobe size and the measure magnetic field strength (17 nT) given for the tail lobe by SIBECK *et al.* (1985) the tail lobe flux is $5.1 \cdot 10^8$ Wb. At low altitudes the same flux passes through a polar circle of radius 15°. For these estimates we have used the same method as that used by Fairfield.

Figure 3 shows the low altitude, precipitating electron and ion boundaries determined from DMSP measurements from 01:00 UT-10:00 UT. This period excludes the extremely intense polar cap arc event shown in images 8 and 9 in Fig. 2. The boundaries plotted in Fig. 3 are the equatorward boundary (black dots), the transition boundary (x's) and the equatorward polar rain, or polar cap boundary (open circles). Here we see that the polar cap, as determined by polar rain, is highly variable. The variability is greatest on the morning side of the oval. All ISEE 3 measurements made on January 15, 1983 were in the dawn sector. The northern polar cap is more symmetric about the magnetic pole than the southern polar cap, but if one encompasses the points nearest 09:00 UT in each hemisphere by a circle, its radius would be less than 15° (more like 12°) MLAT. The transition boundaries, on the other hand, are considerably more stable during this period, and more symmetric with respect to dawn and dusk. For much of the period the transition boundary in both hemispheres, and on both dawn and dusk flanks is at ~70° MLAT, giving an open field region as determined by the transition boundary of 20° MLAT. Near 09:00 UT the dawnside southern transition boundary contracts poleward to 76° MLAT while the dusk boundary remains near 70° MLAT. Thus the open field line region of the cap by these estimates is a circle of radius of 17–18° MLAT. To bring the high and low altitude modelling efforts into agreement requires that between 20–30% of the open field line flux is lost through the magnetopause by 200 R_E, which is rather large. Still, the transition boundary gives a more realistic flux comparison to the ISEE 3 measurements than the polar rain boundary for which flux would have to be *added* with downtail distance to obtain agreement.

Thus, from magnetic flux considerations at low and high altitudes we conclude that the transition boundary gives a better measure of the total magnetic flux found in the tail lobes at 200 R_E. Furthermore, since the tail lobe was still in existence at 200 R_E for periods in which arcs were found in the polar caps we can also conclude that if the

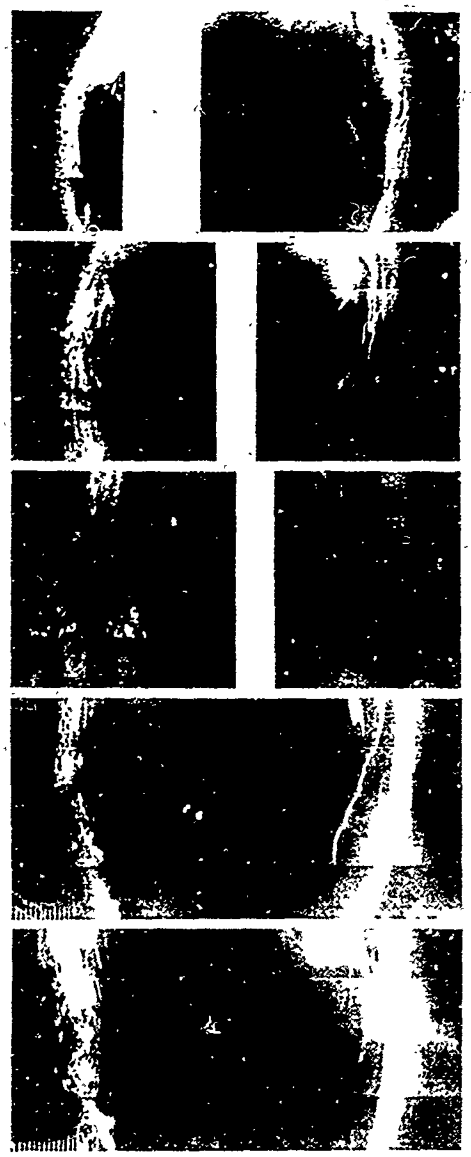

Fig. 2(a). A series of DMSP white light images taken from 00-07 UT on January 15, 1983, and separated by 100 min. In each image midnight is toward the top and dusk toward the right. The time interval for each image and the closest approach of the subsatellite track to the magnetic pole are listed at the right.

magnetic field lines in the magnetosphere become completely closed during polar cap arc occurrence the closure occurs beyond 200 R_E.

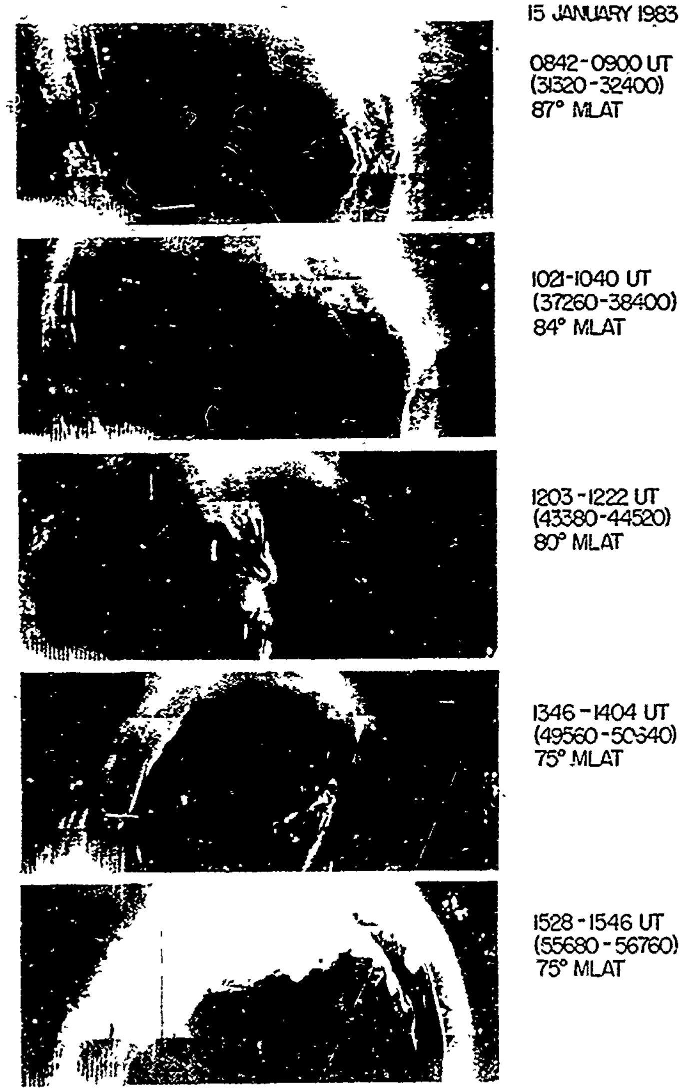

Fig. 2(b). Same as for Fig. 2(a), only for 08 16 UT.

4. Timing

Both precipitating electron profiles measured onboard low altitude satellites (HARDY *et al.*, 1982) and ground observations of polar cap arcs at 83.6° invariant latitude (TROSHICHEV *et al.*, 1988) have been used to estimate the time interval from the northward turning of the IMF to the onset of polar cap arcs, and the time interval between the southward turning of the IMF and the disappearance of polar cap arcs. There is a pronounced asymmetry between the two. The former (time of onset) is longer; an hour or more. The latter (time for clearing) is, on average, 10–20 min (TROSHICHEV *et*

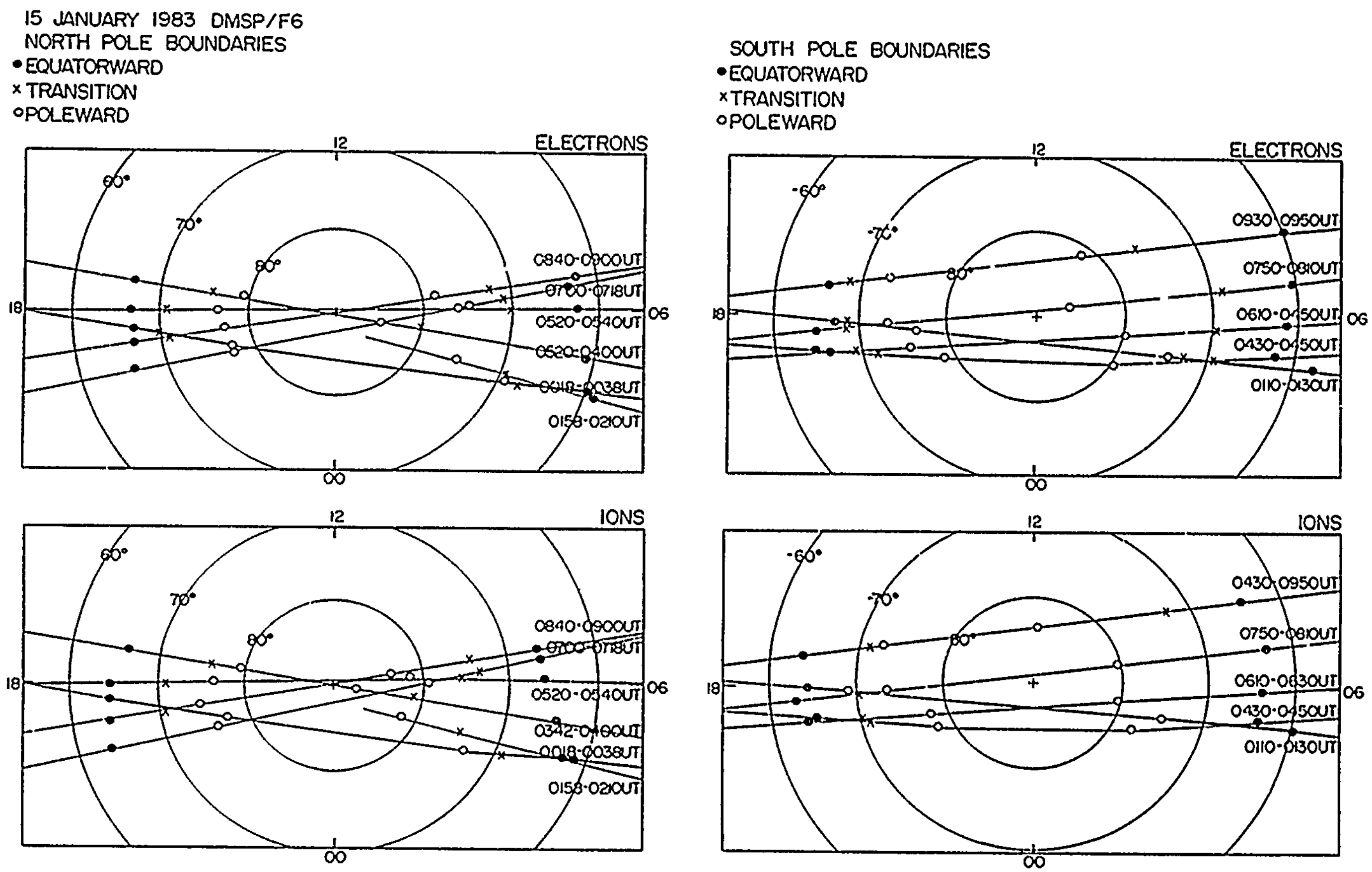

Fig. 3. Electron and ion equatorward, transition and poleward boundaries from 01–10 UT on January 15, 1983. The boundaries are plotted on satellite tracks in corrected geomagnetic latitude and magnetic local time coordinates.

al., 1988). If the twin assumptions hold, namely that the existence of polar cap arcs indicates closed field lines, and the existence of an "empty" cap (e.g., occurrence of polar rain) indicates open field lines, then the observed characteristic transition time for clearing the polar cap is in conflict with a magnetotail longer than 200 R_E for B_z north conditions. We reach this conclusion because the newly southward directed IMF must be carried to the far reaches of the tail at the solar wind speed in order to open the magnetosphere.

To show this, assume that B_z has been northward for a sufficiently long time to fill the polar cap with arcs and close almost all polar cap field lines. Designate the furthest downtail extent of the closure by L. For complete closure L is identical to the tail length. Let B_z turn southward and be carried by a solar wind speed of 600 km/s (greater than the average speed) from the dayside magnetopause down the entire distance L (to open all field lines and bring in polar rain). If we require that this be done in 20 min then L must be $\sim$100 R_E. For slower solar wind speeds or shorter clearing times, L will be considerably smaller. There is no evidence to date that the magnetosphere ever terminates within 100 R_E downstream. In fact, ISEE 3 observations taken near apogee ($\sim$200 R_E) show that a well-formed magnetotail, with magnetopause, plasma sheet and tail lobe, is virtually always present (TSURUTANI *et al.*, 1984). And, as was shown in the previous section, for at least one case of B_z strongly northward, the tail lobes were clearly present at $\sim$200 R_E. Thus, to be consistent with the measured time to clear the cap we can conclude a) that we have somehow missed observing a greatly shortened magnetotail; or b) that polar cap arcs can occur on open field lines; or c) that polar rain entry can be initiated on closed field lines. We take assumption b) since it requires fewer revisions to our current understanding of magnetospheric dynamics.

The onset time for polar cap arcs, namely 1 hr, also has some interesting consequences. In 1 hr a 600 km/s solar wind carries IMF information about 300 R_E downtail. It takes a 1 keV ion another hour to travel this same distance back along a tail magnetic field line. During this time the ion can move 5 to 10 R_E toward the plasma sheet (magnetopause) in a moderately large dawn to dusk (dusk to dawn) convection electric field. Thus, the keV ion mobility is too small to allow ions to respond to large-scale, distant, topological changes in the magnetic field fast enough to play a major role in polar cap arc dynamics. In the next section we review the evidence of RICH *et al.* (1990) that boundary layer ions do play a major role. These ions either enter the magnetosphere Earthward of $\sim$150 R_E or are omni-present by 300 R_E. Closure of field lines well beyond 300 R_E will, therefore, be without influence on ions that accompany polar cap arcs. Because magnetic field closure is without influence to this important component in the polar cap arc dynamical process it calls into question the need for such a major topological change at all.

5. Boundary Layer Plasmas

The particle populations that are found in the polar caps and the tail lobes should provide strong evidence for determining polar cap arc dynamical processes. It has been shown by HARDY *et al.* (1982) and HARDY (1984) that the electrons that are found in the polar caps during IMF B_z northward (polar showers or polar cap arc populations) have weakly accelerated spectra from a low temperature thermal base, e.g., $kT\sim$100 eV. This is the same thermal base found for polar rain. Thus aside from their field aligned accelerations, the electrons in the polar cap have the characteristics of boundary populations whose primary source is the magnetosheath. (Note that we do not exclude secondary ionospheric or magnetospheric sources which also find their way into the magnetosheath and reappear in boundary layers.) In the past most attention to particles accompanying polar cap arcs has been given to electrons. There is, however, a significant ion population that reaches to very high latitudes in polar cap arc occurrence. The ions are principally in the 1–10 keV energy range (GORNEY *et al.*, 1986). They have mass composition similar to that of neighboring high latitude oval populations (PETERSON and SHELLEY, 1984; FRANK *et al.* 1986). Along the field lines at low altitude the polar cap ion spectra can be fit to streaming Maxwellians (RICH *et al.*, 1990).

The case study by RICH *et al.* (1990) concludes that the ions found at very high latitudes during polar cap arc events are boundary or magnetosheath populations. The case they studied was a very intense polar cap arc event that occurred in the midst of the development of the major magnetic storm of February, 1989. This event followed the one studied by GUSSENHOVEN and MULLEN (1989). It is notable for its size, as determined by field aligned currents and particle precipitation levels, and by the rapidity with which the magnetosphere changed from a state of intense, expanded oval activity to one of weak oval activity and strong polar cap activity. The precipitating particle and magnetic current characteristics found for this event are as follows: 1) At the onset of the event the equatorward auroral oval boundary (which we equate to the inward edge of the central plasma sheet, [CPS]) contracted sharply. This was accompanied by a weaker contraction of the electron transition boundary (poleward edge of the CPS and equatorward edge of the boundary plasma). That is, the combined boundary motions indicated that the low altitude width of the central plasma sheet decreased significantly, rather than expanded into the polar cap. 2) Ions above the electron transition boundary on the dayside (including the region of the cusp) expanded into the polar cap at the same time arcs, visible in white light images, filled the polar cap. (In Fig. 1 ion expansion also accompanies polar cap arcs, but here it appears to emanate from the nightside.) These ions, like the electrons, have boundary layer, or magnetosheath-like spectra. At the low energy end they are well-fit to low density streaming Maxwellians in the one direction of observation (downward, along magnetic field lines) with bulk flows of several hundred km/s and temperatures of several hundred of eV. At the high energy end they are Maxwellian with temperatures of several keV and densities from 0.1–1.0 cm^{-3}. These are magnetosheath and boundary layer ion characteristics, not CPS ion characteristics (EASTMAN *et al.*, 1985). 3) The nightside region 1 and region 2 field aligned currents (FAC) disappeared as the polar cap event developed, but the boundary layer ions expanding from the dayside into the polar cap brought with them extremely intense NBZ currents (IIJIMA *et al.*, 1984) in the southern (summer) hemisphere. For a similar satellite path traversed in the northern (winter) hemisphere, the polar cap FACs were of quite different structure. The difference could not be readily explained by the conductivity differences of the two hemispheres. Thus, the FAC in the polar cap appear to be driven in a distinctly non-conjugate way. (Note the GUSSENHOVEN and MULLEN (1989) also showed that the ion penetration to high latitudes in their polar cap arc event was non-conjugate.)

The study of RICH *et al.* (1990) gives results that are quite contrary to the notion that the closed field line region of the magnetosphere either expands systematically to extremely high latitudes or bifurcates the high latitude region during polar cap arc occurrence. Instead, the central plasma sheet diminishes, the transition boundary remains relatively constant, and the boundary plasma, carrying field aligned currents, expands to extremely high latitude in a distinctly non-conjugate way.

6. Summary and Discussion

In this review of recent work done on polar cap arc and/or high IMF B_z events we have attempted to look at as many magnetospheric features as possible to examine evidence for and against total magnetic field line closure at these times. We find the following:

1) Relativistic solar electrons and polar rain give very different pictures of the low altitude region of the open field lines, under the assumption that each population gains entry to the magnetosphere on open field lines.

2) There is no evidence, either from substorm processes or from direct measurements, that the distant tail flux ever falls to low enough values to correspond to a nearly closed magnetosphere.

3) The observed timing for the decay of polar cap arc occurrence is inconsistent with a long, closed magnetotail. The observed timing for the onset of polar cap arc occurrence rules out distant closure of magnetic field lines from having any effect on ion dynamics of polar cap arcs.

4) The particle signatures in the polar cap are those of the boundary plasma not those of the central plasma sheet. We find evidence for non-conjugate processes in the polar cap during polar cap arc events.

We have argued that the electron transition boundary is a better approximation to the open-closed magnetic field boundary than the polar rain equatorward boundary, or equivalently the auroral arc poleward boundary. At low altitudes the transition boundary marks the boundary between magnetosheath-like populations and warmer populations associated with the central plasma sheet. Magnetosheath-like populations are found in the dayside cusp and cleft, at high latitudes along the dawn-dusk flanks (also called the low latitude boundary layer) and on the nightside above the central plasma sheet (also called the boundary plasma sheet). Although these boundary populations have been observed for years, we are only beginning to document their systematic responses to changes in interplanetary conditions. Understanding of the entry and transport processes of these populations is still primitive. Quite clearly, the boundary populations expand poleward at low altitudes when B_z is northward, the flank populations most notably so. It is not clear whether the expansion indicates a different entry mechanism than occurs for B_z southward or whether it indicates a different transport process within the tail lobes. In requiring that the magnetospheric magnetic field close to explain the boundary layer expansion into the caps, emphasis is placed on the boundary layer entry mechanism. We have shown here that many problems arise in that scenario. Transport differences in the tail lobes for B_z northward and southward have been investigated to an even lesser degree, even though low energy populations are not the same at high and low altitudes. Here low energy ions play an influential role in the physical processes of the near and distant tail lobes because of their low mobility. A significant problem is the redirection of boundary layer ions from streaming away from the Earth to streaming toward the Earth or in both directions. This problem is present regardless of the sign of B_z since the flank populations occur for all activity conditions (HARDY *et al.*, 1989).

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